Improving Competitive Status of Oak Regeneration Using Stand Management and Prescribed Fires

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The effect of prescribed fire characteristics and timber harvest treatments on top-kill and resprouting in northeastern deciduous hardwood forests was compared among species groups (oak, maple, birch) and size classes to determine if the competitive status of oak regeneration could be enhanced. Prescribed fires were completed in three distinct stand structures (treatments): recent shelterwoods, recent clearcuts, and stands with significant mountain laurel understories. In each burn, fire behavior was monitored on 3-8 plots (15x15m) using thermocouples arrays. All stems ≥ 140 cm tall within each plot or ≥ 6 cm dbh within 15 m of plot centers were examined for girdling and the number and height of new sprouts during the second growing season after the fire. Top-kill did not vary among species groups and could be described by a logistic function that included treatment, initial stem size, and maximum temperature. Apparent top-kill increased with thermocouple maximum temperature, decreased with stem size, and increased from shelterwood to clearcut to mountain laurel understory burns. Proportion of top-killed stems with new sprouts was greatest for mountain laurel and oak. A combination of stand manipulation and prescribed fire can improve the competitive status of oak seedlings by modifying regeneration composition and height distribution.

KEYWORDS. *Acer*, *Betula*, height growth, mortality, prescribed burns, *Quercus*, survival

INTRODUCTION

Fire has been an integral disturbance factor in the eastern deciduous forests, certainly since the arrival of European colonists (Clark, 1970) and presumably before (Day, 1953; Abrams, 1992). Aggressive fire exclusion programs that were initiated in the early 1900s (Tillotson, 1916; Stickel, 1939) are thought to be one factor in the conversion of many oak (*Quercus* spp.) stands to more mesophytic stands throughout the region (Van Lear & Waldrop, 1989; Nowacki & Abrams, 2008). Loss of an oak component will not only have economic ramifications, but it will affect regional wildlife populations dependent on oak mast (Rodewald, 2003).

Use of prescribed fire as a tool to enhance oak regeneration has had mixed success (Arthur, Alexander, Dey, Schweitzer, & Loftis, 2012), and there appear to be different regional responses to single, low-intensity burns. On unmanaged upland forests with higher site quality, the effect of a single, low-intensity fire on increasing the competitive status of oak regeneration has been at best neutral, and often detrimental, because of vigorous resprouting and recruitment of new seedlings by non-oak species (Swan, 1970; Nyland, Abrahamson, & Adams, 1982; Malsen, 1989; Merritt & Pope, 1991; Moser, 1996; Blankenship & Arthur, 2006). However, on drier, intrinsic oak accumulation ecosystems (*sensu* Johnson, Shifley, & Rogers, 2002, page 121), single, low-intensity fires can benefit oaks by increasing their leaf mass and by reducing the relative size of non-oaks (Little, 1946; Barnes & Van Lear, 1998; Adams & Rieske, 2001).

The competitive status of oak regeneration has been shown to be improved following high-intensity fires resulting in overstory mortality (Brown, 1960; Ward & Stephens, 1989; Moser, Ducey, & Ashton, 1996) or when used in conjunction with an overstory harvest (Brose & Van Lear, 1998; Iverson, Prasad, Hutchinson, Rebbeck, & Yaussy, 2008; Brose, 2010). Perhaps the principal factor for increased survival and growth of oak seedlings following high-intensity fires is increased light following fire-induced mortality of overstory trees (all species) and smaller competing non-oak saplings (Loftis, 1990; Lorimer, Chapman, Lambert, 1994).

It has long been recognized that top-kill (i.e., death of aboveground stems) decreases with increasing stem size (Ferguson, 1957; Loomis, 1973; Dey & Hartman, 2005). Because most smaller stems are top-killed by fire, survival depends on new sprouts that develop from intact basal buds associated with the root collar. Ward and Brose (2004) showed that while more than 95% of seedlings and saplings were top-killed by a prescribed fire, over 84% of oaks and 76% of maples survived by forming new sprouts. Brose and Van Lear (2004) noted the root collar location within the soil/litter interface differed between oaks, red maple (*Acer rubrum* L.), and yellow-poplar (*Liriodendron tulipifera* L.) and that oaks had deeper root collars than other species. Because deeper root collars and associated basal buds were protected from lethal temperatures during fires, oak mortality was lower than for similar sized red maples and yellow-poplars.

There are also physiological differences in the response of oaks and other species to damage caused by fire. Maple seedlings have been found to continue allocating resources to above-ground tissues in an unsuccessful attempt to recover from heat damage, while oak seedlings allocated resources to new sprout production (Huddle & Pallardy, 1996). Relative to oak, maple seedlings have been shown to have poor leaf physiological performance following a prescribed burn (Reich, Abrams, Ellsworth, Kruger, & Tabone, 1990).

Development of accurate models of genera-specific (e.g., oak, maple) responses to burning would provide valuable tools for enhancing oak regeneration using prescribed burning. Ideally, these models would incorporate characteristics of stem (size, species), stand (percent overstory and midstory cover), and fire (intensity, seasonality, return intervals). Logistic regression models have been used to describe post-fire mortality in western conifers (Woolley, Shaw, Ganio, & Fitzgerald, 2012) and eastern hardwoods (Regelbrugge & Smith, 1994; Dey & Hartman, 2005). However, these models have rarely focused on the smaller size classes relevant to the use of prescribed fire to enhance oak regeneration. Logistic survival models that included the heights and basal diameters of advanced regeneration for specific species were developed for the Ozarks (Dey & Hartman 2005).

The primary objective of this paper was to determine the separate and interactive effects of stand manipulation and prescribed fire characteristics on genera-specific probabilities of top-kill and developing new sprouts. Our focus was on the response of small stems and rootstocks found in the regeneration stratum. A parallel objective was to describe the number and height of new sprouts that developed from top-killed rootstocks for each of the dominant genera (oak, maple). Natural resource managers could use these results to determine whether prescribed fire, in conjunction with selective cutting, is appropriate as part of an integrated management prescription to enhance the competitive status of oak regeneration (Arthur, Alexander, Dey, Schweitzer, & Loftis, 2012).

METHODS

Study areas

Seven study areas were established in Connecticut in mature, mixed-oak stands on Connecticut Department of Energy and Environmental Protection (CT DEEP) state forests that originated around 1900 (Table 1). Prior to treatments (below), all study sites were fully stocked upland oak stands. Treatments resulted in one of three distinct stand structures: recent shelterwoods with residual oak overstories, recent clearcuts after shelterwood prep cuts, and stands with a dense mountain laurel understory (*Kalmia latifolia* L.) (Table 1). These treatments were selected as part of a larger regional study with USDA Forest Service scientists to develop improved fire behavior models.

Following treatments and before prescribed burning, white oak (*Quercus alba* L.), northern red oak (*Q. rubra* L.) and black oak (*Q. velutina* Lam.) were minor components of the regeneration stratum (< 10 cm diameter), except at Salam A. Oak regeneration was mostly overtopped by more abundant red maple (*Acer rubrum* L.), black birch (*Betula lenta* L.), American hornbeam (*Carpinus caroliniana* Walter), mountain laurel, and other species.

Prescribed fires

Prescribed burns were conducted on the seven sites in spring 2003 and spring 2004 (Table 2). Fuels consisted of leaf litter, hardwood slash on the harvested sites, and on some sites, ericaceous shrubs. Weather data collected at one minute intervals using a Hobo ® weather station included: temperature, relative humidity, and wind speed.

Within each of the seven sites, 3-8 fire behavior measurement plots measuring 15 m x 15 m were established. Each plot (see below) was inventoried for fuel cover, height, and loading by type and size class using twelve 4.6-m (15-foot) sampling transects (Brown, Oberhau, & Johnston, 1982). Fire behavior (temperature, duration) at each plot was monitored using an array of five thermocouples with data loggers (Hobo ® thermocouple logger H12-002, Onset Computer Corp., Bourne, MA) per array. Each array consisted of a 15 m by 15 m square with thermocouples at each corner and in the array center (Fig. 1). Each stainless-steel thermocouple probe (Hobo ® Type K 12" –TCP-K12, 0.6 mm diameter, Onset Computer Corp., Bourne, MA) was attached by a buried lead to a data logger with the thermocouple junction approximately 25 cm aboveground. Temperatures were recorded at 1.5 second intervals. Maximum thermocouple temperature was considered an index of plant tissue heating. Where possible, flame heights were visually assessed. Heavy smoke and erratic fire behavior precluded visual monitoring of rate-of-spread. Therefore, rate-of-spread was estimated by using the time it took for the temperature to reach 60^{o}C between each thermocouple and the distance between thermocouples.

CT DEEP - Forestry Division personnel conducted all burns using drip torches to ignite a backing fire along the downwind side of the site perimeter within the fire break to create a black line. Once a secure black line was established, flanking fires were lit along each side. A head fire was ignited once adequate black lines were secure on three sides. Internal strip fires were not needed and would have exceeded safety parameters due to heavy slash, flammable shrubs, and, in some cases, erratic fire behavior and discarded ammunition.

Vegetation

The effect of the prescribed fires on vegetation was assessed during the second growing season after the fires, approximately sixteen months post-fire. The following information was recorded for all stems at least 140 cm tall within each 15 m x 15 m plot and all stems $\geq$ 6 cm dbh within 15 m of a plot center: species, height to a maximum of 200 cm, diameter breast height (dbh, at 1.4 m aboveground in 0.1 cm increments, 1.0 cm minimum), stem girdle (10% increments), post-fire sprout (yes/no). Both single stems and stems that were part of a sprout clump prior to the prescribed fires were tallied. Stems with no live leaves on an original stem, or that were at least 90 percent girdled, were classified as top-killed. For all rootstocks that had a new sprout, the height of the tallest sprout (cm) and number of sprouts were recorded. Sampling sixteen months after the fires introduced a bias because some smaller stems were destroyed by the fires and some stems died of causes other than the fire. Post-fire sampling reduced inevitable trampling damage that would be caused by pre-fire sampling, especially in denser regeneration patches.

Data analysis

Logistic regression was used to determine the effects of initial size, species group, treatment, and thermocouple temperature on probability of top-kill and forming a new sprout. For logistic regression, tallied stems with diameters less than 1 cm (i.e., diameter was not recorded) were assigned approximated diameters based on height class (<150 cm tall – 0.1 mm dbh, 150 cm tall

– 1.5 mm dbh, 160 cm tall – 3.0 mm dbh, 170 cm tall – 4.5 mm dbh, 180 cm tall – 6.0 mm dbh, 190 cm tall – 7.5 mm dbh, ≥200 cm tall – 9.0 mm dbh). Species were categorized into six groups for analysis: Maple, Oak, Birch, Other trees (*Carpinus*, *Prunus*, *Ostrya*, *Castanea*, *Carya*, *Cornus*, *Sassafras* and others), Shrub (*Corylus*, *Hamamelis*, *Vaccinium*, and others), and mountain laurel.

Logistic regression analyses (SYSTAT 13, San Jose, California) were used to model 1) probability of top-kill and 2) probability of top-killed plants not forming a new sprout (i.e., whole plant death), with treatment (stand structure) and species group as categorical independent variables and initial (pre-burn) stem size and maximum thermocouple temperature as continuous independent variables. While full models and subsets were examined, only parsimonious models with the lowest Akaike's Information Criterion (AIC) are presented. Note that the probability of top-killed plant not forming a new sprout is synonymous with the root stock being dead and that the probability of a top-killed plant forming a new sprout was calculated as: P(top-killed with new sprout) = 1 – P(top-killed without new sprout).

To determine the potential effects of treatment, species group, maximum thermocouple temperature, and initial size on resprouting, a two-factor ANCOVA with covariates (General Linear Model, SYSTAT 13, San Jose, California) was run with to examine the effect of each variable on: 1) number of new sprouts per top-killed stem, and 2) height of the tallest new sprout. Treatment and species groups were categorical factors, while temperature and size as covariates. Tukey's honestly significant difference (HSD) test was used to test differences of number of new sprouts and sprout heights among species groups over combined treatments. Differences were considered significant at P = 0.05.

RESULTS

A total of 3,476 stems across six species groups (34 species total) were tallied (Table 3). The full logistic model estimate of top-kill that included species groups had a higher AIC (1865.4) than the selected model shown below. The only species group that was significant in the full model was Shrub (p=0.0432). Significance of other species groups ranged from p=0.1130 to p=0.8684. Therefore, we selected the more parsimonious model without species group as a factor (i.e., combined species groups) that had a lower AIC (1803.2) was selected:

$$\text{Top-kill (\%)} = e^x / (1+e^x) \qquad \text{Equation 1}$$

where x = 0.522 + TRT + 0.0056*MaxTemp (^{o}C) – 0.298*dbh (cm), and TRT=0, 0.514, and 1.801 for shelterwoods, clearcuts, and mountain laurel stands, respectively (Chi-square=1628.9, df=4, p<0.001). This model indicated that top-kill increased with maximum temperature (Fig. 2a), decreased with initial size, was higher in recent clearcuts than recent shelterwoods, and was highest in stands with significant mountain laurel cover (Fig. 2b).

The proportion of top-killed stems that produced new sprouts varied greatly among species groups (Table 4). Over all treatments, mountain laurel had the highest proportion of top-killed stems that produced a new sprout (76%) and birch had the lowest proportion (20%). Indeed, few birch taller than 160 cm produced a new sprout and less than 10% of top-killed birch with a diameter greater than 5 cm resprouted.

The logistic models that best described the proportion of top-killed stems that did not produce sprouts (i.e., dead rootstocks) differed greatly among species groups (Table 5). Pre-burn treatment (stand structure) was a significant factor for oak, birch, and shrubs. The proportion of top-killed oaks with no sprouts was highest in shelterwood, intermediate in clearcuts, and lowest in mountain laurel stands; the converse was observed for birch and shrubs. While the analysis indicated that the proportion of top-killed without new sprouts decreased with increasing maximum temperature for the birch and other species groups, the odds ratio confidence intervals that nearly straddle 1.0 suggest these results could be spurious (Table 5). For three species groups (maple, shrub, other), the proportion of top-killed stems that produced new sprouts increased with diameter. Top-killed maples were more likely than oaks to have new sprouts in shelterwoods (Fig. 3).

Based on the ANCOVA, the number of new sprouts from top-killed stems varied among treatments ($F=4.80$, $df=2$, $p=0.008$), species groups ($F=32.52$, $df=5$, $p<0.001$), and increased with maximum temperature ($F=8.06$, $df=1$, $p=0.005$) and initial size class ($F=86.63$, $df=1$, $p<0.001$). Tukey's HSD tests indicated that the average number of new sprouts in shelterwoods (12.2) was higher than in clearcuts (9.4). Birch averaged the lowest number of new sprouts and mountain laurel had the highest (Fig. 4).

Height of new sprouts from top-killed stems varied among treatments ($F=191.8$, $df=2$, $p<0.0001$) and species groups ($F=17.75$, $df=5$, $p<0.001$), but not by maximum temperature ($F=0.20$, $df=1$, p=0.653) or initial size class (F=0.199, df=1, p=0.665). Tukey's HSD tests indicated that the height of tallest stems decreased from clearcuts (90 cm) to shelterwoods (54 cm) to mountain laurel stands (37 cm). Except for shorter birch and mountain laurel, heights of new sprouts did not differ among species groups (Fig. 5).

DISCUSSION

Stem size

This study found that oak, maple, birch, and associated trees and shrubs in an eastern deciduous forest vary in their probability of surviving prescribed fire depending on pre-burn stem size, species, maximum thermocouple temperature, and stand structure. Survival is defined as the stem being less than 90% girdled by a fire, or if top-killed, producing a new sprout from the rootstock. The observation that top-kill decreased with increasing stem size (Fig. 2) was consistent with earlier reports for upland hardwoods (Loomis, 1973; Alexander, Arthur, Loftis, & Green, 2008). Except in very severe fires, most stems with diameter greater than 10 cm were not top-killed (Fig. 2).

In contrast, other studies reported smaller stems were resistant to top-kill during prescribed fires, but whether this difference was due to differences in fire intensity or genetic variety between regions could not be ascertained. A Texas study found the diameter at which half of hardwoods were top-killed by burning in an immature loblolly-shortleaf pine stand was approximately 5cm and few oaks larger than 15 cm were killed (Ferguson, 1957). Examining survival, which includes stems not top-killed and top-killed stems that produced new sprouts, Dey and Hartman (2005) reported most oaks with a basal diameter greater than 4 cm survived prescribed fires in Missouri. I found that tree size was a significant factor in logistic regression models describing top-kill (Equation 1), similar to studies of logistic regression models in Virginia and Missouri that found tree size was negatively correlated with top-kill (Regelbrugge & Smith, 1994) or survival (Dey & Hartman, 2005).

Species

Top-kill rates did not differ among species in this study. This may have been a bias of having a relatively small sample size in the larger diameter classes for some species groups (Table 3). An earlier Connecticut study also reported that seedling top-kill did not differ among oak, red maple, and black birch seedlings (< 1 cm dbh) (Ward & Brose, 2004). In contrast, top-kill of saplings (< 10 cm dbh) was lower for oak than for red maple and other species in mixed-oak forests in New York (Swan, 1970), Wisconsin (Reich, Abrams, Ellsworth, Kruger, & Tabone, 1990), and Virginia (Regelbrugge & Smith, 1994). In a North Carolina Piedmont upland hardwood forest, top-kill of stems 2-15 cm dbh was lower for oaks than non-oaks, but did not differ between species for stems shorter than 4 m (Malsen, 1989).

Rootstock survival after top-kill varied among species groups (Table 5). As found in other studies (Brose 2012), black birch was particularly susceptible to whole plant death, especially in the larger size classes (Table 4). For a given initial size class there was little difference between oak and red maple in the proportion of top-killed individuals that produced new sprouts. Similarly, after fire in New York northern hardwood, all red maples and nearly all oak saplings produced new sprouts after top-kill (Swan, 1970). A North Carolina study reported that a higher proportion of top-killed oak saplings (< 4 m tall) produced new sprouts than non-oaks saplings (Malsen, 1989). However, an earlier study of prescribed burning in recent Connecticut clearcuts observed oak seedlings resprouted at higher rates than red maple and that few top-killed black birch (< 25%) produced new sprouts (Ward & Brose, 2004). Oaks are more likely to have basal buds that survive fires and produce new sprouts because most oaks, but not red maples, have buried root collars (Brose & Van Lear, 2004).

Prescribed fires appear to 'level the playing field' with respect to height of new sprouts as there was no difference in new sprout height among oaks, red maples, and miscellaneous tree species (Fig. 5). When oaks have the same height as competing species following prescribed fires, oaks can be expected to grow faster than other species that: (1) utilize root carbohydrate resources to maintain compromised aboveground tissues rather than for new sprouts (Huddle & Pallardy, 1996) or (2) have reduced leaf physiological performance following fire (Reich, Abrams, Ellsworth, Kruger, & Tabone, 1990).

Other studies showed that height growth of oak sprouts relative to other species was improved 2 years (Ward & Brose, 2004), 5 years (Malsen, 1989; Alexander, Arthur, Loftis, & Green, 2008; Abrams & Steiner, 2013), or 11 years after a prescribed fire (Brose 2010). Without prescribed burning, oak seedlings grew slower than their competitors (Malsen, 1989; Brose & Van Lear, 1998; Alexander, Arthur, Loftis, & Green, 2008). It should be noted that the above studies and the current study did not have intact overstories, except for Alexander, Arthur, Loftis, & Green (2008). These findings are in contrast to studies where the overstory was continuous and prescribed fires did not enhance the competitive status of oak (Nyland, Abrahamson, & Adams, 1982; Albrecht & McCarthy, 2006).

Maximum temperature

Top-kill increased with maximum thermocouple temperature as an indicator of plant tissue heating (Fig. 2a). For example, using equation 1, the estimated diameter at which half of the stems were top-killed (D-TK_{50}) ranged from 4.4 cm for low temperature burns (60^oC) to 9.1 cm for high temperature burns (300^oC) in shelterwoods. Inferring fire intensity by bole blacking, Loomis (1973) reported similar, slightly higher D-TK_{50} ranging from 5 to 25 cm.

Maximum measured temperature was found to influence the rate at which birch and other (miscellaneous) hardwoods developed new sprouts, but not oak and maple (Table 5). Similarly, fire intensity had no effect on red maple and red oak seedling survival in a Kentucky study (Alexander, Arthur, Loftis, & Green, 2008). In contrast, red maple survival was inversely related to fire intensity in Virginia (Brose & Van Lear, 1998). Oak sprouts may outgrow sprouts of maples and other species where fire resulted in high overstory mortality (Alexander, Arthur, Loftis, & Green, 2008), but where fires were light and had little impact on the overstory, oak will remain suppressed under the shrub layer (Moser, Ducey, Ashton, 1996).

Stand structure

Stand structure appeared to be an important predictor of both top-kill in general and the proportion of top-killed plants resprouting in the case of birch and oak. As noted in Results, top-kill for a given maximum measured temperature was greatest in stands with mountain laurel understories and least in shelterwoods (Equation 1, Fig. 2b). While some fire characteristics (e.g., maximum temperature, rate of spread, flame height) were generally greater in stands with mountain laurel (Tables 1 and 2), the casual mechanism(s) for differences in species response among stand structures is unclear because the models also included a maximum temperature component (Equation 1, Table 5). While speculative, the physical structure of dense evergreen canopies in areas with mountain laurel may have delayed vertical dispersal of heated air and thereby increased convective heat transfer to lower stem boles.

Management implications

This study indicates that prescribed burning, in conjunction stand manipulation, could be used to increase the competitive status of oak regeneration (Arthur, Alexander, Dey, Schweitzer, & Loftis, 2012). This recommendation is predicated on the presence of larger established oak regeneration prior to the burn (Brose & Van Lear, 2004). Where oak regeneration is present, prescribed fires can increase the competitive status of oak in two ways. First, burning will largely eliminate established seedlings and small saplings of fire sensitive species such as birch and yellow-poplar (Brose & Van Lear, 1998; Ward & Brose, 2004). Second, burning will top-kill seedlings and saplings of species competing with oaks, and the new sprouts of non-oak species will be of similar size to oak sprouts (Fig. 5). It should be noted that the new sprouts of competing species will not only no longer be overtopping oaks, but they will also be much smaller horizontally, allowing increased side light on oak regeneration. If the overstory is not open prior to burning, additional stand manipulation will be required to provide sufficient light for the oaks to remain competitive (Arthur, Alexander, Dey, Schweitzer, & Loftis, 2012).

The observation that after a prescribed fire the proportion of maples that produced a sprout increased with initial size suggests a strategy of cutting maples with diameters larger than 5 cm at least one growing season prior to the prescribed fire to reduce the absolute number of red maples that sprout. The relatively small new sprouts that develop from the cut stumps will be susceptible to top-kill during a subsequent fire. In addition, any new sprouts of non-oak species that emerge after the prescribed fires will be of similar size to the new oak sprouts (Fig. 5), ultimately providing an advantage to oaks as described above. This 'leveling of the playing field' increases the relative competitiveness of oak sprouts relative to other species as compared to conditions prior to fire

Lastly, the findings of this and other studies suggest a non-traditional use of prescribed fires, namely, burning young clearcuts several years after final overstory removal, rather than the more traditional use of fire following a shelterwood cut (Brose 2012). Prescribed fires in young stands 3-10 years after clearcutting were reported to improve the competitive status of oaks in Connecticut (Ward & Brose, 2004), Wisconsin (Kruger & Reich, 1997), northwestern (Brose, 2012) and central Pennsylvania (Abrams & Steiner, 2013), but not in Alabama except with an extremely hot fire (McGee, 1979). Although shelterwood cuts may result in the development of larger oak seedlings, all too often, especially on higher quality sites, the oak is overtopped by species with faster juvenile height growth. If managers suspect that oak regeneration will remain overtopped by established non-oak competitors after the final harvest, or that oaks will be overtopped by species with faster juvenile height growth (e.g., birch, yellow poplar), a rough fire break could be established around the perimeter of the clearcut during the harvest operation. Thus, if an inventory several years after the harvest determined oak was being overtopped, the roughed-out fire breaks would minimize site preparation prior to burning. Because the prescribed fire would occur at the stage of stand development when stems would be top-killed and sprouts would develop from root collars, the stems that would develop into the future forest would not have fire scars and associated internal decay. Although this approach will delay stand growth for several years, the long-term benefits of accomplishing higher oak dominance for both economic and ecological objectives are likely to outweigh the cost of a slightly longer rotation.

Results of this study reiterate the potential use of occasional fire in northeastern deciduous forests to promote the establishment and development of competitive upland oak regeneration. Fire may be especially important in the wake of disturbances (whether human or natural) that reduce or eliminate canopy cover, when competitive interactions among species have strong long-term effects on forest stand composition.

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Table 1. Stand structure of prescribed fire study areas in Connecticut.

Study area name	Lyme	Haddam	Goodwin	Chester	SalemA	Jericho	SalemB
Location (town)	Lyme	Haddam	Chaplin	Chester	East Lyme	Haddam	Salem
Structure*	Clearcut*	Clearcut	Shelter	Shelter	MTL	MTL	MTL
Years since last harvest	5	2	6	1	7	uncut	8
Number of Plots	4	4	4	3	8	2	5
Basal area (m^2/hectare)							
10-25 cm dbh	0.6	0.8	5.4	0.5	4.1	2.7	5.9
25-50 cm dbh	0.8	1.9	9.4	8.4	15.0	9.9	16.5
> 50 cm dbh	0.0	0.0	3.9	7.0	1.6	2.1	4.4
Total	1.4	2.7	18.8	15.9	20.7	14.7	26.8
Regeneration density (stems/hectare)**							

< 2.5 cm dbh	10,033	2,133	2,456	1,896	2,050	600	1,956
2.5-10 cm dbh	836	585	357	715	1,438	103	1,997
Regeneration distribution							
Oak	11%	3%	13%	0%	26%	0%	1%
Maple	14%	26%	23%	19%	3%	0%	12%
Birch	5%	5%	35%	6%	5%	6%	5%
Other trees	51%	32%	14%	49%	2%	3%	3%
Shrubs	20%	34%	15%	26%	64%	91%	79%
Mountain laurel cover (%)	0	27	0	2	37	65	54

*Clearcut – most sawtimber (>25 cm dbh) removed in final harvest after a shelterwood prep cut, Shelter-existing shelterwood, MTL – plots with more than one-third mountain laurel cover.

**Regeneration – stems with diameters less than 10 cm.

Table 2. Fuels, weather, and fire characteristics of prescribed fires in Connecticut.

Study area name	Lyme	Haddam	Goodwin	Chester	SalemA	Jericho	SalemB
Area burned (hectares)	8	3	2	8	8	4	7
Burn date	14-Apr-03	16-Apr-03	1-May-04	19-Apr-04	30-Apr-03	29-Apr-03	30-Apr-04
Pre-burn fuels (metric tons/ha)							
Litter	10.5	10.3	11.7	11.2	10.2	12.3	9.6
1-hour)	0.2	0.4	0.1	0.7	0.2	0.4	1.6
10-hour	2.2	2.7	1.1	6.0	1.3	1.6	1.6
100-hour	7.0	8.7	5.5	21.5	5.7	3.1	10.5
Total	19.9	22.1	18.5	39.4	17.5	17.7	23.3
Weather							
Air temperature (^{o}C)	12.2	17.2	23.9	17.2	20.0	23.3	21.7

Relative humidity (%)	22	38	46	36	25	20	48
Windspeed (m/s)	1.3	1.8	1.3	1.8	1.3	0.2	1.6
Fire behavior (mean)							
Maximum temperature (^{o}C)	78	201	143	156	196	203	204
Seconds > 60^{o}C	1.5	6.2	3.5	5.3	5.5	3.7	5.5
Rate of spread (m/hour)	159	94	119	48	224	603	69
Flame height (cm)	60	60	30	60	150	150	90
Char height (cm)	23	66	28	79	74	109	55
Fire behavior (range)							
Maximum temperature (^{o}C)	46-360	42-654	91-252	36-742	87-499	136-287	83-448
Seconds > 60^{o}C	0-6	0-19	2-18	0-17	3-10	3-5	3-10
Rate of spread (m/hour)	90-230	50-150	60-150	25-90	45-575	405-860	50-90

Flame height (cm)	0-90	0-180	30-300	0-180	60-300	60-450	30-90

Table 3. Distribution of tallied stems by species group and size class for combined study areas.

Size class (cm)	Oak	Maple	Birch	Other	Mt.Laurel	Shrub	Total
140-160 tall	33	48	30	92	69	111	383
160-200 tall	85	144	77	330	126	187	949
1.0-2.4 dbh	114	77	39	190	233	75	728
2.5-4.9 dbh	62	46	20	69	285	57	539
5.0-9.9 dbh	37	68	58	70	88	13	334
10.0-14.9 dbh	17	53	41	36	1		148
15.0-19.9 dbh	21	36	30	4			91
20.0-29.9 dbh	46	34	36	13			129
>=30.0 dbh	136	8	18	13			175
Total	551	514	349	817	802	443	3476

Table 4. Proportion of top-killed stems with new sprouts by species group and size class for combined study areas.

Size class (cm)	Oak	Maple	Birch	Other	Mt.Laurel	Shrub	Total
<160 tall	63%	51%	47%	31%	74%	50%	51%
>160 tall	55%	42%	25%	30%	72%	42%	42%
1.0-2.4 dbh	68%	52%	16%	51%	68%	42%	57%
2.5-4.9 dbh	77%	73%	19%	63%	83%	50%	74%
5.0-9.9 dbh	74%	63%	6%	82%	87%	91%	67%
>= 10.0 dbh	70%	96%	9%	42%			56%
Combined	66%	57%	20%	40%	76%	47%	55%

Table 5. Logistic model* parameter estimates (SE) for the proportion of top-killed stems that did not produce new sprouts (i.e., root stock killed by prescribed fire). OR – Odds Ratio 95% confidence interval.

Estimates	Oak	Other	Birch	Maple	Shrub
Constant	1.170 (0.382)	1.347 (0.197)	1.754 (0.580)	0.252 (0.132)	n.s.
	p=0.002	p< 0.001	p=0.002	p=0.056	p=0.309
Trt-CC**	-1.470 (0.435)	n.s.	1.928 (0.570)	n.s.	n.s.
	p< 0.001	p=0.153	p< 0.001	p=0.934	p=0.927
	OR: 0.10-0.54	OR: 0.98-2.41	OR: 2.25-21.01	OR: 0.60-1.75	OR: 0.56-1.71
Trt-MTL	-2.492 (0.421)	n.s.	2.570 (0.528)	n.s.	1.169 (0.342)
	p< 0.001	p=0.095	p< 0.001	p=0.243	p< 0.001
	OR: 0.04-0.19	OR: 0.87-5.87	OR: 4.64-36.75	OR: 0.74-3.22	OR: 1.64-6.29
Size	n.s.	-0.103 (0.042)	n.s.	-0.180 (0.033)	-0.359 (0.102)
	p=0.311	p=0.014	p=0.624	p< 0.001	p< 0.001
	OR: 0.98-1.07	OR: 0.83-0.98	OR: 0.91-1.06	OR: 0.78-0.89	OR: 0.57-0.85
MaxTemp	n.s.	-0.0027 (0.0006)	-0.0036 (0.0015)	n.s.	n.s.
	p=0.313	p< 0.001	p=0.021	p=0.697	p=0.0928

	OR: 0.993-1.002	OR: 0.996-0.999	OR: 0.994-0.999	OR: 0.999-1.002	OR:0.998-1.000
Chi-square, df	46.8, 2	36.8, 2	39.1, 3	47.3, 1	20.8, 3
P	<0.0001	<0.0001	<0.0001	<0.0001	0.0001

Top-killed stems without new sprouts (%) = $e^{g(x)}$ / (1+$e^{g(x)}$), where x = Constant + p1 (treatment) + p2(size, cm dbh) + p3*(Maximum temperature, ^{o}C) and p1, p2, p3 are parameter estimates.

**Trt-CC – clearcut, Trt-MTL – mountain laurel understory, Trt-Shelt – shelterwood which served as reference and had a parameter estimate of zero.

Figure 1. Schematic showing location of thermocouples (vertical lines) and areas sampled from all stems > 140 cm tall (white) and stems > 6 cm dbh (grey).

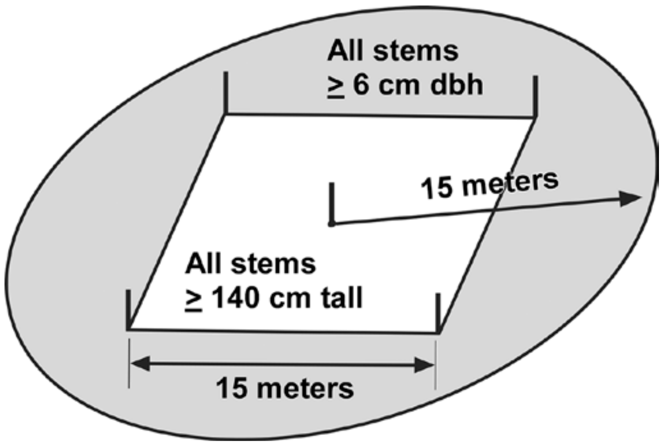

Figure 2a. Estimated stem top-kill by maximum temperature and initial size using Equation 1

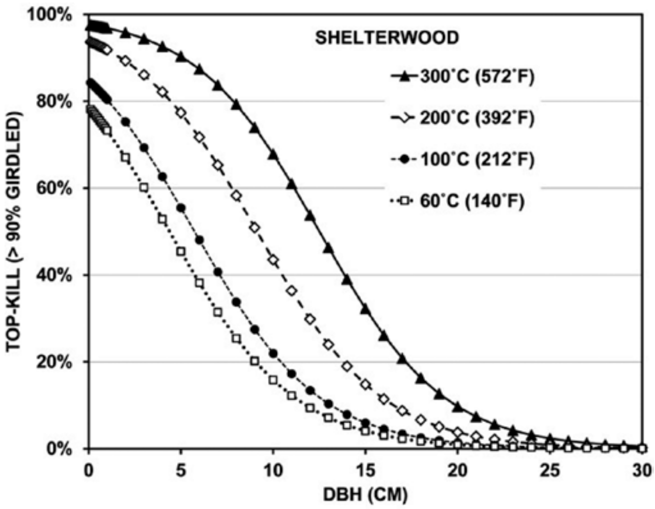

Figure 2b. Estimated stem-top-kill for moderate intensity fires by stand structure and initial size.

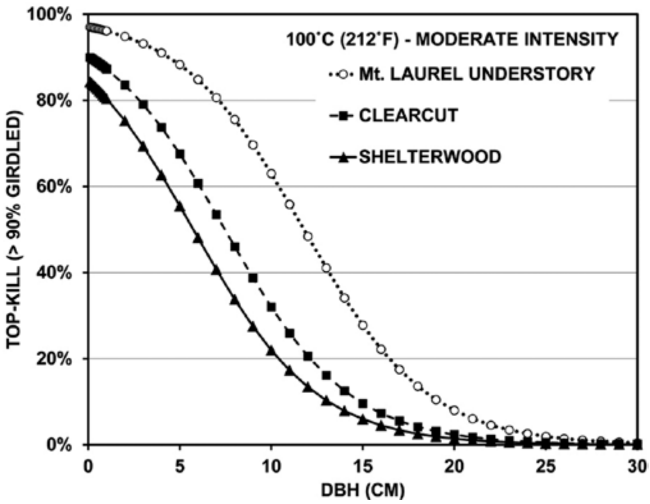

Figure 3. Comparison between oak and maples on proportion of top-killed stems that produced new sprouts Shelt-shelterwood burns, CC-clearcut burns, MTL-mountain laurel understory burns.

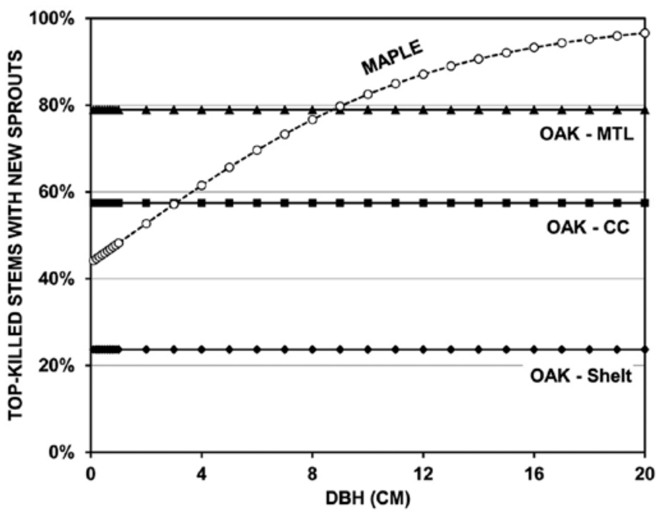

Figure 4. Mean (SEM) number of sprouts produced by top-killed stems by species group. Letters indicate significant differences at P = 0.05.

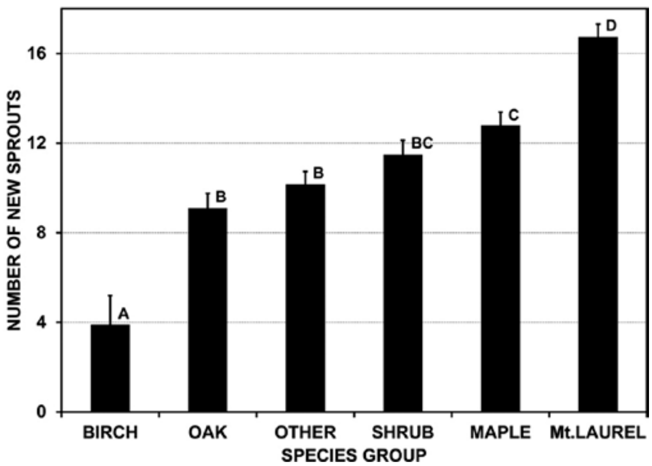

Figure 5. Mean (SEM) height (cm) of tallest new sprouts. Letters indicate significant differences at P = 0.05.